6. Electricity & Magnetism

(multiple choice questions changed 23 March 2006)

Miscellaneous Facts

Electricity is …

… the cause of lightning, which has power greater than a nuclear power plant
… used for all the computations done in a laptop computer
… used for radio communication, and to send telephone signals through wires
… the most convenient (if not also the cheapest) way to transport energy
… able to enter our homes when needed by the flick of a switch, through nationwide circuitry so complex that it can collapse in a few seconds
… so safe that we have outlets all over our homes, and yet it is still used as a gruesome method of execution for humans, and for one "bad" elephant
… used by the nerve cells in our bodies to send signals
… responsible for nuclear fission energy, since the fission fragments get their energy from electric repulsion

The twentieth century could rightly be called "The Century of Electricity." (Of course, it might also be called "The Century of Autos" or of Airplanes or of Antibiotics.) Most of what we call "high-tech" consists of the enslavement of electricity to do our purposes.

Equally mysterious are magnets. They also play a central role in our high-tech world.

Magnetism is…

… the force that runs "electric" motors
… used to store information on computer hard drives
… the main way used to generate electricity
… what Saddam Hussein planned to use to get U-235
… used to determine the ages of sedimentary rocks
… used to run loudspeakers and earphones

Moreover, radio waves, light wave, x-rays, and gamma rays carry half of their energy in electricity and the other half in magnetism.

We now know that magnetism is a subtle aspect of electricity. But what is electricity?

Electricity

Electricity usually means the movement of electrons. (It can also be the movement of protons.) These tiny particles, about 1/2000 of the mass of ordinary materials, can exert huge forces on other objects. We call that the electric force. It is this force and a related force called magnetism that makes electricity so important.

Take two electrons and place them a centimeter from each other. Make sure nothing else is around. Since each has mass, the force of gravity will attract the two electrons to each other. But the electric force between them is repulsive; it pushes them apart. Moreover, this repulsive force is stronger than the attractive gravity force by a factor of approximately

4170000000000000000000000000000000000000000.

I wrote the number that way to be dramatic; the same number can be written as 4.17×10^{42}. So this electric force *completely* overwhelms gravity.

Now consider an electron placed a centimeter from a proton. They will attract each other, not repel. Yet this force will be *exactly* the same as the repulsive force between two electrons.

Electric Charge

The property of the electron that gives its force has a name: the electric "charge." By convention, the charge of the proton is

$$q_p = 1.6 \times 10^{-19} \text{ Coulombs.}$$

You won't need to know that number. The charge on the electron is exactly opposite that on the proto; it is

$$q_e = -1.6 \times 10^{-19} \text{ Coulombs.}$$

By putting the minus sign in front, we keep track of the fact that the force it exerts is opposite to the force exerted by a proton.

If we combine an electron with a proton to make a hydrogen atom, the total charge is 0. So the hydrogen atom does not "feel" an electric force from other particles, since the force on the proton and the force on the electron will be opposite and cancel each other. We say that the ***hydrogen atom is neutral***.

Physics slang: most electricity comes from protons or electrons, so we tend to think in terms of their charges. We will often say the charge of the proton is +1, and the charge on the electron is –1.

Neutrons have mass similar to that of the proton, but neutrons have charge 0. Why? Is it possible that the neutron is similar to a hydrogen atom? A hydrogen atom consists of a proton with charge +1, and an electron with charge -1, and the two cancel. Could a neutron also have interior charges that cancel?

We now know that the answer is *yes*. The neutron consists of three *quarks*. One of them is the u quark (also called the "up" quark), and the other two are d quarks (for "down"). The u quark has a charge of +2/3 (in terms of the proton charge), and each of the d quarks has charge –1/3. So the total neutron charge is 2/3 – 1/3 -1/3 = 0 proton charges. That's why the neutron is neutral.

The proton consists of u u d, with a total charge of 2/3 + 2/3 -1/3 = +1 proton charges.

Charge Is Quantized

As far as we know, all charges in nature are exact multiples of the quark charge. We don't know why. This is stated in physics by saying "charge is quantized." Particles can have charge -1/3, +1/3, 1, 2, etc., but cannot have charge 1/2, 4/5, or 1.22. We don't know why this is true.

You might guess that the reason is that all particles are made of quarks. But that isn't true. Electrons are not made of quarks.

A new and, as of yet, unproven theory is that all particles are made of objects called "strings." If this theory is true, then the reason behind quantization is simply that all particles are really made of the same kind of thing.

Amps of Electric Current

When charged particles move, we call it electric current, in analogy to water current. For water, we measure current in gallons per second, or in cubic meters per second. For electric current, we measure current in electrons per second. A more practical unit is the ampere, or amp. One amp is 6×10^{18} electrons per second. (Don't memorize this number, but you should know that the current is a measurement of electrons per second.)

The current that flows through a light bulb is typically about one amp. Wires in your house carry up to about 15 amps. The current is divided among all the systems that use electricity, such as your refrigerator, lights, TV, and computer. One bolt of lightning has thousands of amps.

Electron pipes and return paths

Metals have a wondrous property: electrons can flow easily right through the solid inside of a piece of metal. (Glass has a similarly wondrous property: light can pass right through it.)

Recall from Chapter 4 that the nucleus takes up very little space in an atom, no more than a mosquito takes in a football stadium. The rest of the space is taken up by electrons. For metals, one of the electrons in each atom is not permanently attached, so it can move from one metal atom to another.

Electrons can move easily inside a piece of metal, but they can't easily leave the surface of the metal. They are held back by the attraction of the positively-charged nuclei. Free movement of electrons can take place only if the moving electrons are replaced by other electrons. For this reason electric current usually flows in circles or closed paths.

Have you noticed that most electric cords (e.g. those for a lamp) have two wires in them? The second one is for the electrons to return. Some computer wires are called coax cables. They also consist of two conductors, but instead of two wires, they have one wire surrounded by a cylindrical metal tube. (Coax derives from coaxial; it means that the axis of the wire is the same as the axis of the tube.) The tube serves as the electron "return path."

When a bird lands on an electric power line, some electrons will immediately flow into the bird. But with nowhere to go, the electrons soon repel other electrons from coming, so the flow will stop. Very few electrons are needed to stop the flow.

Likewise, if a person hanging on an electric power line were to touch nothing else, he would be safe. If he touches another wire (which could be the return path for the electric power) then a large current could flow through him.

Watch a mechanic attach a wire to an automobile battery. He'll be careful not to touch anything else, particularly not the metal of the car, with his other hand. That's because of the fact that one side of the battery is usually attached to the metal of the car, and the mechanic does not want his body to serve as a return path. A car battery can deliver 100 amps of electric current, and that can be dangerous.

Even though the electrons in electric current move in circular paths, they can be used to carry energy and information. As electrons move through wires, you can remove some of the energy from them, such as a mill wheel can take energy from a stream of water. To send information, you vary the amount of current flowing in the circle. In a similar way you can signal someone with a hose by turning the water on and off. Telephone wires carry sound signals by varying the current to match the vibrations of sound.

Resistance

The easiest way to remove electron energy from current is simply from the friction caused by the electron flow. Such friction is called electric *resistance*. Some metals, such as tungsten, have lots of resistance. The filament of an ordinary incandescent light bulb is made of tungsten. When current flows through it, the resistance (friction) heats the filament enough to make it glow. Thus electric current is first turned into heat and then into light. (We'll discuss this more in the next chapter.)

Of course you don't want to heat the wires that go to the bulb, so those are usually made out of copper or another metal with low resistance.

Materials that conduct electricity well (but with resistance) are called **conductors**. Materials that don't conduct electricity very well (such as plastics, rocks, or wood) are called **insulators**. But in between metals and insulators is a group of mysterious materials called **semiconductors**. These are materials that can be made to turn from conductors to insulators and back, by applying electricity in a special way. Their ability to control electric flow is what makes them so useful in electronics from stereo systems to computers. We'll discuss these in more detail in Chapter 10.

Fuses and circuit-breakers

Wires in your house are typically made out of copper, a metal with low resistance, so that they will not waste the energy of electric current. If the current is high, however, then the wires can get hot enough to start a fire in the walls. For this reason, most house wiring has a device that prevents the current from exceeding a safe value, typically 15 amps (enough for about 15 light bulbs.) The two kinds of devices used are called fuses and circuit breakers.

A fuse is a short length of high-resistance material that melts when too much current flows through it. When it melts, it breaks the connection of the wires, and the current stops flowing. To get the current flowing again, the fuse must be replaced. In common usage, to "blow" a fuse means to send enough current through it that the metal inside melts or vaporizes.

A circuit breaker has a wire formed into a bimetallic strip (see Chapter 2). When the bimetallic strip heats beyond the allowed limit, it bends away and breaks the connection to another wire. Unlike the fuse, the circuit breaker can be reset (the bimetallic strip placed back in contact with the wire) after it has cooled.

Superconductors

Superconductors are materials that have zero resistance--they don't impede electricity at all! Rings of superconductors have had currents flowing in them for decades, with no energy source. (The phenomenon is similar to the Earth going around the Sun; if there is no friction, it will just go on forever.)

Unfortunately, all known superconductors have the zero resistance property only at low temperatures. If we could find or manufacture a "room temperature" superconductor, it would revolutionize the way we use electricity. Right now, much energy is wasted by conducting electricity through resistive wires, and a real room-temperature superconductor would revolutionize the way energy is transported.

How can electrons flow inside a metal with zero friction? The answer was not known for many decades, but we now understand that the secret lies in quantum mechanics. We'll discuss this further in Chapter 10.

Superconductors and helium

The easiest way to cool a wire is to put it in a cold liquid. The original superconductors were kept cold by immersing them in liquid helium. The liquid is made in special refrigerators, and then transported to the customer in dewars (glass containers that are similar to "Thermos" bottles). Liquid helium boils at a temperature of 4 K, i.e. only 4 degrees above absolute zero. So as long as there is liquid helium, the temperature is low. Recall from Chapter 4 that helium comes from alpha particles in the Earth's crust, and we collect it from oil and natural gas wells. When these wells run out, we will have no further source of helium. (The Sun is 10% helium, but that's not easy to get.)

Thirty years ago, most of the helium from wells was discarded, because the need for it wasn't great enough to justify the expense of trapping it. United States law now requires the oil and gas companies to recover and store the helium, because of anticipated needs for future superconductors.

Superconductors with nitrogen?

In 1987, the Nobel Prize in physics was awarded to Georg Bednorz and Karl Muller for their discovery of certain compounds that become superconducting at relatively high temperatures. Right now, the highest temperature superconductor works at a temperature of about 150 K, equal to –123 C or –189 F. That's pretty cold for something called "high temperature," but it is the best anyone has done.

Part of the reason scientists use the word "high" for this temperature is that it's higher than the temperature of liquid nitrogen, which is 77 K. Recall that nitrogen is about 80% of air; it is extremely abundant, especially when compared to helium. Nitrogen can be liquefied for about a dollar a quart, making its cost comparable to that of milk (and some bottled water brands). Superconductors that can be kept sufficiently cold with liquid nitrogen are, in principle, much more practical.

So why aren't we using such superconducting wires for all of our power transmission? The answer is that the high-temperature superconductors are all pretty brittle, and it has been difficult to manufacture useful wires from them. Nevertheless, it is being done for some special applications. An experiment to see if such wires can be used for commercial electric power transmission is currently underway by the Detroit Edison power company.

Of course, if liquid nitrogen is used for cooling, then some power is lost--the power needed to produce replacement liquid nitrogen when it boils off. So such transmission lines do use energy.

There is a limit to the amount of current that superconducting wires can carry. That's because high current creates very strong magnetic fields (to be discussed shortly), and strong magnetic fields can destroy superconductivity just as much as can high temperatures. The current they carry depends on the cross-sectional area; some materials have been reported that can carry several million amperes per square centimeter of area.

Amusing fact: according to theory, highly compressed hydrogen should become a metal. It is even possible that the core of the planet Jupiter consists of superconducting hydrogen.

Volts and Electron Energy

Amps tell you how many electrons are flowing past a point each second. Volts tell you the energy of the electrons. The energy unit called the electron volt or eV is defined[1] as

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ joules}$$
(don't memorize)

Whereas the Calorie is a typical amount of chemical energy for a gram of material, the eV is a typical amount of energy for a single atom or molecule. (Memorize!)

Jargon: If a piece of metal has a large number of electrons, each with energy of 1 eV, you'll hear people say that the metal *is at* one volt, or sometimes they'll say it has a *voltage* of one volt, or maybe that it has a *potential* of one volt. It is OK to refer to the energy of an electron in volts, rather than in eV. Physicists will use these two terms slightly differently, but it is not important here. Remember that when a piece of metal is at one volt, it means that every electron in that metal has that energy.

Here are some key numbers about volts:

typical kinetic energy of an electron in an atom	1 volt
TNT energy per molecule	1 volt
flashlight battery	1.5 volts
U.S. house voltage	120 volts
European house voltage	240 volts
voltage inside CRT (television or computer)	50,000 volts
alpha particle from nucleus	1,000,000 volts

Low volt electrons are not very dangerous. A flashlight battery has a typical voltage of 1.5 V. You can read that on the label. It produces electrons with an energy of 1.5 V. You can hold such a battery in your hand with no danger; if you touch the metal leads to your tongue, you'll feel a tingle. Don't do that with a higher voltage battery or the higher energy electrons might burn your tongue.

Finger sparks and static electricity

The sparks that sometimes fly from your finger to a doorknob are often called *static electricity*. It occurs because your feet rub on the ground in such a way that electrons come off and stick to your body. These electrons are static in the sense that they stay there, on your body, until you walk up to a good conductor like a metal doorknob. You'll

[1] The V in eV is usually capitalized. The justification is that it was named after a person, Alessandro Volta. Yet the word *volt* usually is not capitalized. The traditions are not consistent.

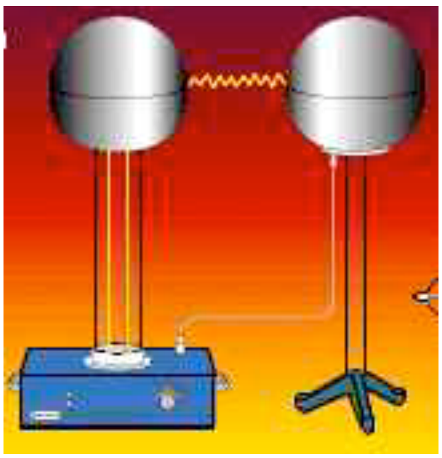
pick up even more electrons if you rub your shoe on a thick carpet. You can also rub electrons onto a comb by running the comb through your hair. Try doing that--run the comb through several times quickly, and then put the comb near some very small (mm size) pieces of paper. The electrons on the comb will attract the bits of paper.

If the air is moist, the static electricity leaks off your body into the air. But on a very low humidity day (which means there is very little moisture in the air) the air is a poor conductor, and the electrons stay on your body. They can move around inside your body, since your salty blood is a pretty good conductor of electricity. But when you have these excess electrons and you put your finger near a piece of metal, they will jump off, creating the flow of current we call a spark.

For that spark, the voltage was probably between 40,000 and 100,000 V! Yet it doesn't kill you because the current is low, limited by the small number of electrons you picked up. Yet a similar voltage in the back of a TV set is very dangerous. That's because the amount of current that can flow to you is much greater.

To know the power, you must know the energy per particle AND the number of particles per second. The same is true with flowing water: you need to know the velocity of the water AND the number of gallons flowing every second.

Finger sparks can be automated for a physics demonstration by using a device called a Van de Graaf generator. In this device, a band of rubber rubs against a piece of wool continuously and the charge is taken off by a wire attached to a metal sphere. In a few seconds the sphere can reach 100,000 V. Yet the sparks are not dangerous because the amount of charge is so small.



Electric Power

The power delivered by electrons depends on the energy of the electrons, and the number per second that arrive. The first is the voltage, and the second is the current. Multiply these together and you get the power.

Let's do this calculation for a small, 1-volt battery delivering 1 amp. The energy of a 1-volt electron is 1.6×10^{-19} J. The number of electrons per second is 1 amp = 6×10^{18} electrons per second. Multiply these together to get $1.6 \times 10^{-19} \times 6 \times 10^{18} \approx 1$ J/s = 1 watt (W). That's not a coincidence. The numbers were chosen to make this work out exactly.[2] So here is the important conclusion:

Power = Volts x Amps

Here is another practical example: suppose you have a light bulb that uses 110 V, and carries a current of 1 amp. Then the power is 110x1 = 110 W. If you run that bulb for an hour, you use a total energy of 110 watt hours = 0.11 kWh.

Note that high voltage does not always mean high power. If the amps are tiny, then high voltage can be safe.

The energy in finger sparks, and lightning

I mentioned earlier that the energy of electrons in a finger spark can be 40,000 V or more. But there aren't usually very many of these excess electrons on your body, typically not much more than about 10^{12} of them.[3] That may seem big, but it is much less than the number of atoms in a gram of material.

In fact, if those electrons flowed out of at the rate of 1 milliamp (i.e. one thousandth of an amp, one thousandth of the current you get in a light bulb). At that rate, you would run out of electrons in only 1/1000 of a second. The total energy of the electrons is 0.01 J, less than 2 microCalories (2 millionths of a Calorie). It is not important that you know these numbers. It is important for you to know that high voltage is not dangerous if there isn't much current and if it doesn't last for very long.

In contrast to the little finger spark, lightning has both high voltage and high current. For typical lightning values, a million volts at 10,000 amps, we get a power of 10 gigawatts (GW)! That's more than most commercial power plants. If I assume that the lightning lasts for 1/10 of a second, then the energy is 10 GW x 0.1 s = 1 gigajoule (GJ) = 250 million Cal. That's the energy in 250 *tons* of high explosive.

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[2] The energy in 1 eV is not exactly 1.6×10^{-19} J. A more accurate number is that 1 eV $\approx 1.60217733 \times 10^{-19}$ J. An ampere is not exactly 6×10^{18} electrons per second. A more accurate number is 1 amp $\approx 6.2415064 \times 10^{18}$ electrons per second.

[3] For those of you who have studied electrical engineering, here is the way I did the calculation. I assumed the electrons had an energy of V = 40,000 eV. I assume that the capacitance of your hand was about C = 10 picofarads. Then the charge in Coulombs is $Q = CV$. Divide by 1.6×10^{-19} to get the number of electrons. The energy in joules is $E = 1/2\ C\ V^2$.

Sparks, frog legs, and the Frankenstein monster

In 1786, Luigi Galvani, one of the pioneers of electricity, discovered that when he applied small sparks from static electricity to the legs of dead frogs, the legs twitched. Later, he hung frog legs on metal hooks outside his house during thunderstorms. (Electricity was not easy to get in those days; Galvani had not yet invented the battery. But Benjamin Franklin had already discovered that lightning was electricity.)

Galvani thought he had made the frog leg come alive. He hadn't. He had just delivered a signal to the muscle that made it contract. But he believed he had discovered a secret of life, and he called it "animal electricity." For some fascinating drawings of his experiments, look up "Galvani frog" on the web.

In 1817, Mary Shelley, inspired by Galvani's experiment, created one of the first science fiction classics *Frankenstein*. Just as Galvani thought electricity could bring a dead frog leg to life, Shelley's fictional character Dr. Frankenstein thought he could bring a dead person to life by using lightning.

The story of Frankenstein became a symbol of what could happen when scientists develop new technology without anticipating its applications. In honor of Frankenstein, today some people use the derisive term "frankenfood" for food that has been genetically altered.

House Power

The electricity that comes to your home is usually kept by the power company at a constant average voltage[4] of 110 to 120 V. If you have no lights turned on, no refrigerator, no heaters, no TV, no anything, the voltage is still 120 V--although the current is zero. The power company works very hard to keep the voltage at 120 V even when you start using more appliances. The voltage doesn't change, only the current. The power you use is equal to P = volts x current, with volts = 120, so in the US, your power is

Power (in watts) = 120 x current (in amps)

Appliances are usually marked with their power requirements in watts. If you want to figure out how many amps they take, just divide the power by 120 V.

household amps = watts/120

A bright light bulb that uses 120 W takes 1 amp. A heater that uses 600 W takes 5 amps. Amps add (they represent the number of electrons per second), so if you have both the

[4] By the "average voltage" I mean the RMS value. If you are interested, RMS stands for root mean square value. It is calculated by squaring the voltage, averaging it (since house current oscillates 60 times per second) and then taking the square root of this average value. In statistics, it is called the variance.

light bulb and the heater, then you will have a total of 1 + 5 = 6 amps coming into your home. If you use more than 15, your fuse might blow.

In Europe, the typical house voltage is 240 V rather than 120 V. That means that for typical power, the voltage is higher and the current is less. Higher voltage makes the electricity more dangerous than in the U.S., but lower current means that there is less energy lost in the wires that deliver electricity to the outlet. (Or, alternatively, it means that they can use cheaper wires without getting too much heating.)

If you want to keep a 15 amp fuse from blowing, then you should limit the power of your electric appliances to 15 amps x 120 V = 1800 W. One electric heater can use this much. Appliances such as toasters tend to use high current for short periods, but that is enough (when used together with a heater) to blow a fuse.

High tension power lines

Most long-distance transmission of electricity is done at extremely high voltage, several tens of thousands of volts. At these high voltages, you can sometimes hear the crackle of small sparks coming from the wires. Sometimes people refer to these lines as "high tension" lines. That's not because people who live near them get tense, but because "tension" is an old synonym for voltage.

There is an important reason that we use high voltage for such lines. Recall that power = voltage x current. So high-voltage lines have less current (for the same power delivered) than do low-voltage lines. But heating from resistance depends only on the current, not on the voltage. So if we use high-voltage lines, then we can reduce the amps, and that reduces the loss of power from resistive heating.

Since high voltage can make electricity dangerous, there are special devices that raise the voltage V and lower the current I, while keeping the power P unchanged (i.e. V times I remains unchanged). Such a transformer is called, aptly, a "transformer." We'll talk about how they do their work after we have discussed magnetism. Some transformers are near homes, so they don't lower the voltage until they are as close as possible. Many of these transformers are filled with an insulator known as PCBs.[5] When it was discovered that PCBs can cause cancer, an ongoing campaign began to eliminate these liquids and replace them with something that was less carcinogenic.

[5] PCB stands for "polychlorinated biphenyl." Polychlorinated means the molecule contains multiple molecules of chlorine. Biphenyl means that the organic molecule has two "phenyl" groups attached, each consisting of an oxygen and hydrogen atom. Even most physicists don't know this kind of chemistry. (I had to look it up too.)

Electric Forces at Different Distances

Near the beginning of this chapter, we considered the force between two electrons a centimeter apart. I said that the electric force was stronger than the gravity force by a factor of 4.17×10^{42}.

Now suppose we put the electrons 2 cm apart. The force of gravity is then 4 times weaker (because gravity is an inverse square law). But so is the electric force! Thus the ratio of the electric force to gravity force is still 4.17×10^{42}.

If you put the electrons 1000 cm apart (in empty space, so that there is nothing else interfering) then the ratio is still 4.17×10^{42}. Electric force and gravity both have the same behavior: *increase* the distance by a factor N, and the force of each *decreases* by a factor of N^2. If the distance increases by a thousand (N = 1000), then the force decreases by a million (N^2 = 1000 x 1000 = 1,000,000).

This similarity in the distance behavior has intrigued a lot of people. It means, for example, that an electron orbiting a proton bears a lot of similarity to the Earth orbiting the Sun. That's why you'll often hear people describing atoms as little solar systems. The analogy is not perfect, however, because when you get to the small dimension of an atom, quantum mechanics becomes important.

Magnets

You're probably familiar with magnets, such as those used to stick messages on refrigerators. Magnets are truly strange, and I strongly recommend that you play with several. A magnet will attract a piece of iron, but it can either attract or repel another magnet, depending on the orientation of the two.

According to the ancient author Pliny (who lived from 23-79 AD), the word "magnet" in Latin comes from Magnes, the name of a shepherd who noticed that his iron staff and nails from his boots were attracted to certain rocks.

The simplest magnets have two ends, one of which is called N or the "north pole" (because if you hang it from a string, it will orient itself to face the North Pole of the Earth), and the other called S or the "south pole." Play, and you'll discover that two north poles repel each other, that two south poles repel each other, but that a north pole will attract a south pole. The repulsion seems particularly mysterious, because it is so unlike gravity. But it is very similar to electricity because the like charges repel and opposite charges attract.

Permanent magnets are materials that keep their magnetism. But every time that electric current flows it creates magnetism. A magnet made with electric current is called an electromagnet. You can turn its magnetism on and off by changing the current.

Lodestones and compasses and kissing stones

The first known magnets were natural rocks containing iron ore, known as lodestones. A magical feature of these stones is that if you suspend them (by a string, or by floating them on a piece of wood), they tend to rotate until one end is pointing north. This became an enormously important discovery, since it could be used to tell direction. It was called a "compass" and was so valuable that it was originally a deeply held secret. Even on a completely cloudy day, far out at sea, you could tell which direction was north. The word lodestone derives from the Old English word "lode" which means way or path; a lodestone helps you find your way. The impact that the magnetic compass had on history is difficult to know. In 1620, Francis Bacon ranked it with gunpowder and the printing press as the three inventions that had revolutionized the world. (He must have meant the "recent" world, since he didn't include earlier inventions such as the wheel, or controlled fire.)

For hundreds of years, nobody understood why one end of the lodestone points north. Some people assumed that the lodestone felt some attraction towards the North Star. The secret turned out to be that the Earth itself is a large magnet, and the north pole of the lodestone was being rotated by the magnetism of the Earth.[6] The "north pointing pole" of the lodestone was referred to as simply "the north pole" of the magnet. The other end was called, naturally, the "south pole" of the magnet.

Another major discovery was that new magnets could be made by rubbing iron needles (in one direction only, not back and forth) repeatedly against a lodestone. The needles were called magnets, and you could make as many as you wanted. These could then be used for compasses.

A second magical feature of lodestones is their force of attraction to each other. Because of this property, the Chinese called them *tzhu shih*, which means "loving stone." The French word is similar: *aimant*, literally, "stones that like each other." Of course, the attraction depends on the orientation. Lodestones, placed N to N, or S to S, dislike each other.

Magnetism

We now know that the force of magnets--what we call magnetism--is really another aspect of electricity. It is a force between electric charges that occurs only if the electric

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[6] There are records of magnets being used in China in the first century. The first records in Europe date from a manuscript written in 1187 by Alexander Neckam. In 1600, William Gilbert (the physician to Queen Elizabeth I) figured out that the Earth was a giant magnet. He wrote, in Latin, "Magnus magnes ipse est globus terrestris." That can be poetically translated as, "A magnificent magnet is the terrestrial globe."

charges are moving. For that reason you can think of magnetism as a force that occurs between electric *currents* rather than between stationary charges.

The magnetic force law[7] is similar to the electric force law, and to the gravity force law. It states that if you have two short lengths of wire, each carrying current, then the force between them is inverse-square. That means if you double the distance, the force will weaken by a factor of four. It is more complicated, however, because the force is not a simple one of attraction or repulsion, but can be in a different direction that depends on the orientation of both segments.

To calculate the force between long wires, you have to add together all the forces between each pair of wire segments. For long wires, there are a huge number of such pairs, and that makes the problems complicated. For simple cases (e.g. two long straight wires) the total force can be worked out mathematically; the result is that two parallel wires carrying current in the same direction will attract each other. For more complicated cases, such as wires wrapped in large loops, the calculation is usually done on a computer.

Permanent Magnets

Modern permanent magnets are used for refrigerator magnets, for magnetic compasses, and for door latches. They certainly don't *seem* to have any electric current. Moreover, they don't *seem* to have anything to do with electricity.

But now we know that permanent magnets do get their magnetism from electric currents. But the electric currents are extremely well hidden. The electric currents for permanent magnets are inside the electrons!

It was discovered in the 20th century that all electrons spin. That means that the charge within the electron is also spinning, and that is an electric current. This makes every electron into a tiny magnet.

It is hard to detect this magnetism if a nearby electron is spinning in the opposite direction, because then the magnetism tends to cancel. This is the case for most materials. But in a few materials, known as ferromagnets (iron is the most prominent example), the electrons from different atoms tend to line up and have the same spin direction. Then the magnetism adds. These are the materials from which we make permanent magnets. They are permanent, because they retain their magnetism without any need for additional power.

You can imagine why it was hard to discover this. Who could have suspected that electrons--all electrons--spin? In fact, we now believe that it is impossible to stop this spin. Electrons always spin. We can change the direction of their spin, but we cannot stop it.

[7] It is usually called the Biot-Savart Law.

Magnetic monopoles

As I mentioned above, in some ways magnets behave like electric charges. North poles repel, just as like electric charges repel, and opposites attract. This has led many people to speculate that there must be magnetic charges, similar to electric charges. These hypothetical objects are called "magnetic monopoles." Permanent magnets behave as if they have a concentration of such charges at their ends.

Yet we know this is not really true. All present permanent magnets actually work because of currents flowing within their electrons.

If you take a magnetic needle, one end will be the north pole, and the other end will be the south pole. You might think that you can break off the north pole by cutting the needle, but if you do that, new poles form at the broken ends--so each piece continues to have one north and one south pole each. Magnets appear to always have both north and south poles, no matter how they are made. That's because a broken magnet still consists of rotating electric currents, and those always produce north and south poles.

Some physicists have speculated that even though all known magnetism comes from currents, that doesn't mean that magnetic monopoles are impossible. Many projects have been made to search for them, or to try to make them. Some theories (e.g. superstring theories) predict that they should exist, or at least, it should be possible to make them. Searches have been made in materials that have been exposed to extremely energetic collisions, since those may have created monopoles. Materials studied have included lunar rock (exposed to energetic cosmic rays for billions of years) and metals placed at the end of large particle accelerators ("atom smashers").

If magnetic monopoles could be made, they would be valuable. They could be accelerated to very high energy by ordinary magnets, and this could be a convenient way to create radiation (which would have applications in medicine and elsewhere).

The short range of magnetism

Because magnets (until monopoles are discovered) have both north and south poles, once you get a reasonable distance away from one, the two fields cancel. This cancellation tends to make the net magnetic field fall off faster, not with an inverse square law but with an inverse cube law. That means that if you go twice as far away, the force is reduced by a factor of $2^3 = 8$. So when twice as far away, the force is 2x2x2 = 8 times less. If you are three times as far away, the force is 3x3x3 = 27 times weaker.

The result is that magnets are very useful for short distances, but don't work very well for larger distances. You may have noticed this, if you tried to pick up an object with a magnet. Unless the magnet is close to the object, it has very little net force on it.

Electric and Magnetic Fields

It was once thought that one electric charge put a force directly on other electric charges. Now we know that there is something intermediate that happens. The electric charge creates something that we call an **electric field** that fills up space. It is this field that puts the force on the second charge.

Gravity works the same way. Mass creates a gravitational field. When a second object is in that gravity field, it feels a force from the field. In other words, there is not direct force between the two masses. Rather, one mass creates a field, and the other mass feels that.

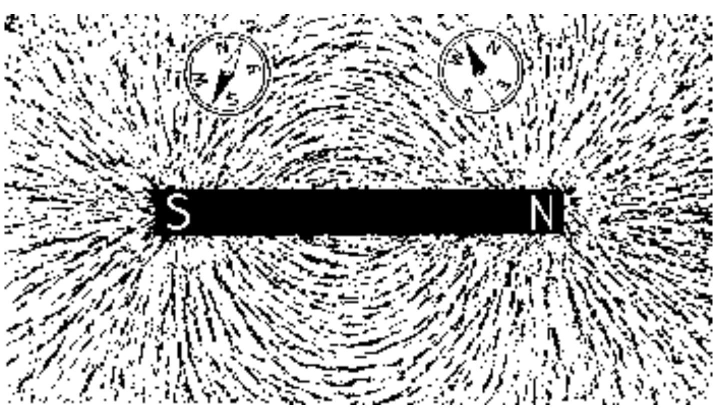
The situation is similar to two people pulling on ends of a rope. One person pulls on the rope, and the rope pulls on the other person. The two people don't directly touch each other.

The way we know electric fields really exist is from the behavior when you suddenly remove one of the charges. The force on the other charge is still there, if only for a short time.

We also know that the field can be made to vibrate, a phenomenon that gives rise to something known as an electromagnetic wave. (This is analogous to shaking the rope.) It turns out that light, radio signals, and x-rays are all examples of electromagnetic waves.

The key idea here is that charge produces an electric field, and this electric field can produce a force on other charges. Likewise, moving charges (currents) produce a magnetic field, and this field can exert a force on other moving charges.

Magnetic fields can be visualized by sprinkling iron filings near a powerful permanent magnet. An illustration of this is shown below. Two compasses have been placed near the magnets that illustrate the direction that they would point.



(Image borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm)

If there is a magnetic field in a vacuum, is it still a vacuum? That is partly a matter of definition. There are no particles there, but the magnetic field does contain energy. Is space really empty if it contains energy?

The magnetic field is easy to visualize because of the way it lines up iron filings. It is possible but much harder to "see" strong electric fields since they tend to produce sparks.

Electromagnets

If you put a wire into the right geometry, you can arrange it to exert a very strong electrical force on other currents, or on a permanent magnet. A common geometry to do this is called a solenoid. It is just wires wrapped around a cylinder. Turn on the electricity, and you have a strong magnet. Turn it off, and the magnet is turned off. Reverse the current, and the magnetism is reversed (i.e. the north pole becomes a south pole).

Electromagnets have lots of uses. In automobiles, they are used to lock and unlock doors. (If you click the door switch, a solenoid electromagnet pulls a permanent magnet.) Small electromagnets are used in speakers and earphones to create sound. Typically such devices have a small permanent magnet, and an electromagnet. Electric current goes through the electromagnet and that causes an attraction between it and the permanent magnet. Then the current is reversed, the magnetism of the electromagnet is reversed, and now the two magnets repel. Usually, the electromagnet is made very lightweight and it can move back and forth in response to these reversing forces. The electromagnet vibrates in a way that follows the oscillations of the current. In an earphone or speaker, a piece of paper attached to the electromagnet oscillates along with it, and that pushes against the air, making the air vibrate. Air vibrations reach the human ear, and we hear them as music. (We'll discuss this further in Chapter 7 "Waves.")

Magnetic Materials--The Special Role of Iron

I said earlier that permanent magnets are made from materials in which a large number of the electrons are spinning in the same direction. Ordinary iron is not normally a permanent magnet because its electrons, even though they are spinning, are all spinning in different directions.

But if you apply an external magnetic field, e.g. by an electromagnet, then that puts a force on these spinning electrons. For iron atoms, it tends to make the electrons all spin in the same direction, and that makes the iron into a magnet, as long as there is current flowing in the external electromagnet. We say that magnetism is *induced* in the iron.

That's why a permanent magnet can pick up a paperclip. When you bring the permanent magnet near the paperclip, magnetism is induced in it, and then the permanent magnet and the paperclip attract each other.

Here is how an electromagnet can lift a piece of iron, as in a junked car. The electromagnet is turned on, and it makes a strong magnetic field. This magnetism aligns the electron spins in the iron of the car, turning it into a magnet. It is an induced magnet. For iron, the two magnets (the electromagnet and the induced iron magnet) attract each other.

Induced magnetism can also be used to make magnetic fields that are much stronger. If you place iron inside the cylinder of an electromagnet, then the weak magnetism of the current is strongly enhanced by the induced magnetism of the electron spins. And it doesn't stop there. The induced magnetism of some of the atoms induces even more electrons to spin in the same way. The strength of the magnetism grows dramatically, until the magnetism is hundreds of times stronger than it would have been without the iron. This kind of magnetic amplification is so useful that most electromagnets use iron cores.

Remnant magnetism

Imagine that you have an electromagnet that is applying its field to a piece of iron. When the electric current is turned off, and there is no externally applied magnetic field, then most of the induced magnetism goes away. But usually some of the electrons remain lined up with each other, so there is a small *remnant* (that means remaining) magnetism.

Remnant magnetism can be very useful, e.g. to make permanent magnets, or it can be a real nuisance. If you bring an iron screwdriver close to a strong magnet, it becomes magnetized; when you take it away, there may be some remnant magnetism left. If that is true, the screwdriver may attract screws or little bits of iron, and that can be useful or annoying. Old watches (in pre-electronic days) would become magnetized if brought close to a magnet, and then the pieces within the watch would attract each other, and that was usually enough for the watch to stop working. Watch repair experts would fix the watch by putting it back in a changing magnetic field that would slowly reduce the magnetization to zero.

Magnetic recording

Induced magnetism is also the basis behind magnetic recording, and that includes videotape, computer hard drives, and MP3 players. In these devices, a very small electromagnet induces magnetism in a small region of a magnetic material. In the adjacent region, it can induce similar magnetism or a reversed magnetism. The signal is stored in the magnetic material by these small regions. For example, if adjacent regions have the upward direction induced in a series of north and south magnetic poles: N, N, S, S, N, then this could be a way of recording the digital signals 1, 1, 0, 0, 1. This is the basic principle for all magnetic recording.

Some magnetic recording devices record this pattern on flexible tape, e.g. cassette players and videotape recorders. The tape has a very thin layer of magnetic material deposited on its surface. To get a lot of information on the tape, the magnetic regions must be very small. A computer hard drive has magnetic material distributed on the surface of a rotating disk. As the disk moves under the electromagnet, different places have different induced magnetism. These days, these regions are typically a micron or smaller in size.

The magnetic recording can be "read" by another wire. When a moving magnet passes a wire, it makes a small amount of electric current flow, and that current can be detected. In modern hard drives the wire is a special material in which the resistance of the wire depends on the magnetic field. By measuring that resistance, the wire gives information about the magnetic field.

Heat destroys remnant magnetism: Curie temperature

If you heat a permanent magnet, the atoms and electrons bounce around faster and faster. This can cause the atoms to change their orientation, and the electrons within them to change the direction of their spin. Pierre Curie, the husband of the more famous Madam Marie Curie, discovered that at a certain temperature all permanent magnetism disappears (since the electron spins get mixed up). Every material has its own "Curie temperature" at which this happens.

Remember this: if you heat up a permanent magnet to its Curie temperature, then its magnetism goes away.

Rare earth magnets

In the last few decades, a particularly strong type of permanent magnet was invented. The first was made out of a compound called samarium cobalt. Samarium is an element known as a "rare earth." Since its discovery, other similar compounds have been found, and these magnets are often called "rare earth magnets."

These magnets are so strong that they can be dangerous. If you break one (maybe by dropping it) and it breaks in such a way that the two pieces repel each other, then pieces can go flying apart at such high velocities that they can hurt someone. When used in earphones, they are packaged in such a way as to prevent the magnet from being struck with a shattering blow.

A few years ago, earphones were big and bulky. Now, thanks to rare earth magnets, high quality earphones can be small and light. Similarly for loudspeakers and motors.

Finding submarines

A submarine is made of steel, and when it sits in the Earth's field, it becomes a big magnet. During World War II, scientists realized that you might be able to find submarines deep under water by detecting this magnetism. Because magnetic fields get weak at large distances (by a factor of $1/r^3$), this method doesn't work for very deep submarines, but it is still used when submarines are within a few hundred meters of the surface.

Because this method works so well, submarines are specially treated every time they come to port to remove any remnant magnetism they may have picked up.

Electric motors

Electric motors are really based on magnetism. In an electric motor, the wires are wound in such a way as to create a strong magnetic field. In the simplest version of a motor, this magnetism is used to pull or push on a permanent magnet. If the current is reversed, then the permanent magnet can be made to move in a circle. That is how an "electric" motor works.

It is not necessary to use a permanent magnet. Many electric motors use two electromagnets, one which is stationary and one which rotates. The electric current is switched in such a way that the force of one magnet on the other pushes the rotating magnet in circles.

As long as thick wires are used, the electric resistance can be small, and electric motors can be very efficient, i.e. they can turn the electric power into mechanical motion with very little loss to heat. Hybrid automobiles use the electricity stored in batteries to drive the wheels with electric motors.

Electric Generators

The most effective way to make electricity for commercial use is by moving a wire through a magnetic field. When this is done, it is called an electric generator. Essentially all the electricity that you use is made this way. You also use some electricity from batteries (in flashlights and in your auto), but that is only a very little bit compared to the rest.

A wire made of metal has electrons in it that can move. When you move this wire through a magnetic field, then the electrons move with the wire. Moving electrons, just as with any current, feel a force from the magnetism. If you move the wire perpendicular to the length of the wire, then the force of the magnetism will be along the wire, so the electrons will be pushed along the wire--that is, current will flow along the wire.

At nuclear power plants, the nuclear chain reaction is used to produce heat, and that turns water into steam. The steam drives propellers (technically called a turbine) and those are used to drive wires through a magnetic field, producing electricity.

In a coal burning power plant, the coal is burned to produce heat--and from there on, the power plant works the same way, ultimately producing electricity by pushing wires through a magnetic field.

In a gasoline burning power plant, or one that uses natural gas, the fuel is burned to produce heat, and from there on the process is the same.

In a hydroelectric plant, water coming from the reservoir is used to turn wheels, and these push wires through magnetic fields, etc., etc.

Once your automobile has started, it no longer needs a battery. From then on, all the electricity it needs (for spark plugs, and to light the headlights) is made from the gasoline engine, which turns an axle called a crankshaft, which turns a wheel that moves wires through a magnetic field.

Dynamos

To work well, a generator needs a strong magnetic field. For small generators, the field can be made out of permanent magnets. But for big generators, the magnets must be electromagnets. Guess where they get the electricity to run the electromagnets.

That's right. They get the electricity from the generator! When this is done, the generator is called a dynamo.

This sounds paradoxical, but it really works. Most large generators are dynamos. It sounds like you are getting something for nothing, but that isn't true. It takes energy to push the wire through the magnetic field,[8] and all the electric energy that emerges (in the current of the wire, and in the magnetic field) comes from the energy that you put in.

The North Pole is a South Pole

As we discussed earlier, the Earth is a great magnet. That's why compasses point towards the poles. But the Earth's magnetism is not perfectly aligned with the axis of the Earth's spin, so the direction that the compass points is not true north but a different location. The magnetic pole is located at a latitude of about 75 degrees, in northern Canada near Baffin Island. Maps often have a little symbol on them that shows the difference between magnetic north and true north.

The situation is much worse on some of the other planets. On Uranus and Neptune, the magnetic poles are 60 degrees away from the poles of the rotation axis.

You should be aware of a semantic problem in our terminology. The north pole of a compass needle points towards the Earth's magnetic pole. But the north pole of a magnet is attracted to a "south pole" of another magnet. Thus, magnetically speaking, the magnetic pole that is up in Canada is really a south magnetic pole!

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[8] The current that flows in the wire interacts with the magnetism, and produces a force that resists the motion. That's why you have to do work to move the wire.

Einstein's mystery

When William Gilbert deduced that the Earth was a magnet, he naturally assumed that it was a permanent magnet, perhaps from large deposits of lodestones. But we now know that rocks below the Earth are hot, from the Earth's radioactivity. At a depth of about 30 km, the temperature is higher than the Curie temperature, so all magnetism must disappear. These paradoxes led Albert Einstein to list the origin of the Earth's magnetism to be one of the greatest unsolved problems of physics.

We now believe we know the answer: the Earth is a dynamo. We don't know in detail how this works, but we understand the general picture. The early Earth (4.5 billion years ago) was very hot, and most of the iron melted and sank to the center. It is still there; if you go about halfway to the center of the Earth, the material changes from rock to molten iron. Moreover, this iron is in constant flow from heat that is being released from a small solid iron core deep within. This flowing iron behaves like a dynamo. When liquid iron moves in a magnetic field, electric currents flow (just as in a moving wire). The arrangement of flow in the core is such that these electric currents circle around to create the magnetic field, just as they do in a commercial dynamo generator.

This picture is verified by computer and mathematical models, but it is hard to be sure, since the center of the Earth is far harder to reach than the surface of the Moon.

The Earth flips--its magnet

As ocean animals die and drift to the bottom of the sea, they eventually form new layers of rock. These rocks become slightly magnetized by the Earth's magnetic field, and then they hold that magnetism for millions of years. If we study the layers of rock, and measure their ages (from potassium-argon dating, as discussed in Chapter 4), we can read the history of the Earth's magnetism.

From these records we have learned that the strength of the magnetic field changes slowly with time. But much more startling is the discovery that from time to time the magnetism of the Earth flips! That means that if you took a present-day magnetic compass back into the past, that the north-pointing needle would point south instead of north.

The last flip was almost a million years ago, and such flips (at least in recent times) seem to occur, on average, once or twice every million years. The flip takes several thousand years to happen, but in the geologic record that seems very fast.

We don't know why the magnetism flips, but several theories have been proposed. It turns out that the actual flow of liquid iron that drives the dynamo doesn't have to change. Instead only the electric current has to reverse. When that happens, the magnetism will flip too. There are some theories that attribute the change to the chaotic behavior seen in some dynamo models.

My favorite theory (also unproven) is that the flip magnetism consists of two steps: a destruction of the dynamo flow (perhaps triggered by avalanches of rock at the liquid/rock boundary), followed by a rebuilding of the dynamo in the opposite direction.[9]

Now here is a riddle, make sense of the following words: "The Earth's North Pole is a south pole. However, about a million years ago, it was a north pole."

Flipping magnetism and geology

The fact that the Earth's magnetism flips every million years or so has been enormously useful in geology and related fields such as climate study. It is valuable because we often cannot measure the age of a rock from its radioactivity. For example, rocks often don't contain enough potassium for the potassium-argon method to be used. However, most rocks formed under the sea preserve a record of the Earth's magnetism. We can see a pattern in the layers, almost like a fingerprint, with some flips coming close to each other in time, and others with wide spacing. Once this pattern is known, then we can correlate the patterns at different locations around the Earth. We don't know how old a layer is, but at least we know it is the same age as another rock somewhere else on Earth.

But we can do even better. If we search long enough, we'll probably find a rock that was formed near a volcano. Volcanic ash contains lots of potassium. If we can use potassium-argon dating to obtain the age of this one rock, then we immediately know the age of rocks all around the world that are at the same position in the geomagnetic pattern.

This is also important because these other rocks often contain unique records of their own. Some of them record the patterns of previous climate. If you put all this together, you can figure out when the last ice age occurred on Earth, how long it lasted, and how quickly it ended. In this way, much of our knowledge of the past has used the Earth's magnetic field flips.

Earth's magnetism and cosmic radiation

Just as electrons flowing in a wire feel a force from a magnetic field, cosmic rays coming from space feel a force and are deflected by the Earth's magnetic field. This prevents a large number of these particles from hitting the top of the Earth's atmosphere. Some people have speculated that when the Earth's field collapses (as during a magnetic reversal) that life on Earth will be exposed to this deadly radiation. This idea has been widely spread by science fiction movies such as *The Core* (2003).

If the field collapses, then it is true that the cosmic rays will hit the Earth's upper atmosphere. But the atmosphere is the true shield, and even without the field, the

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[9] This theory is my favorite, in part, because it is my theory. It was published in the journal Geophysics Research Letters, and is available online at http://muller.lbl.gov/papers/Avalanches_at_the_CMB.pdf.

radiation that reaches the Earth's surface will increase by only a few percent.[10] Thus, the field collapse will not significantly affect life.

Transformers

An electric generator works by moving a wire past a magnetic field. It would work equally well if the magnet were moved past the wire.[11] In fact, the magnets don't actually have to move; it works equally well if their magnetic field is just changing, and that can be done by changing the current in an electromagnet.

If all the ideas in the previous paragraph are put together, we get one of the great inventions of all time: the electric transformer. In a transformer, there is a coil of wire called the primary. Changing electric currents in this primary create a changing magnetic field. The changing magnetic field passes through a second coil of wire called the secondary, and it causes current to flow in the secondary.

One remarkable fact about a transformer is that it can pass energy from the primary coil to the secondary coil very efficiently, with almost none being lost. The primary and the secondary don't touch each other. The energy is all passed through in the form of magnetism!

What makes the transformer so valuable is the fact that the number of loops of wire in the primary and secondary can be different, and the result is that the voltage and current in the two coils will be different. A transformer transforms high voltage electricity to low voltage electricity, or the other way around. It is transformers that take the high voltage from power lines and reduce the voltage to make it safe for our homes. And they all work using magnetism.

If there is any iron near the transformer, then that iron may vibrate as the magnetic field changes. You can often hear a "hum" from a transformer that is doing this. Of course, that hum means that some energy is being lost from electricity to sound, so high quality transformers are built so this doesn't happen.

The Tesla coil

Nikolai Tesla, a scientist who worked with Thomas Edison, invented a very high voltage transformer we now call a Tesla coil. One of his tricks was to make the current change very rapidly, and that generated very high voltages in the secondary. A Tesla coil can be

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[10] At the geomagnetic pole, the Earth's field presently gives no shielding whatsoever. This results in a much stronger cosmic radiation at the top of the atmosphere, and yet the radiation at the bottom of the atmosphere is only slightly greater than elsewhere on Earth.

[11] This is true, but it isn't really obvious. The discovery that it was true was led to Einstein's postulate that the laws of physics are identical regardless of the way you are moving, and that lead him to the theory of relativity.

used for a dramatic demonstration in the classroom, with continuous sparks over a foot long. At the same time, the sparks are not particularly dangerous. When the transformer raises the voltage of electricity, it must also lower the current--since the power is current times voltage, and the power doesn't change. So a Tesla coil can create extremely high voltage sparks, but they release relatively low power.

The demonstrations used in the Berkeley Physics Department can be seen at these web pages:
http://www.mip.berkeley.edu/physics/D+75+04.html
http://www.mip.berkeley.edu/physics/D+75+08.html

AC vs. DC

Most of our homes use alternating current electricity, abbreviated AC. In AC, the current is constantly changing, cycling its flow from positive to negative and then back again, 60 times every second. That's what we mean when we say that house current is 60 cycles--that is short for 60 "cycles per second." There are 60 minutes in an hour, 60 seconds in a minute, and 60 cycles in a second.

A new terminology is to use the name Hertz to mean "cycles per second." Hertz is abbreviated Hz. In the U.S. we use 60 Hz electricity. In Europe, they use 50 Hz.

Batteries give DC, or "direct current." So why do we use AC in our homes? The answer is because AC works naturally with transformers. High voltage (and low current) is used in high tension power lines to bring electricity to our homes. But before it enters the home, a transformer changes it to a relatively low voltage of 110 V and relatively high current of up to about 15 amps.

It was not always obvious that our electrical system would be based on AC. In the late 1800s, Thomas Edison believed the future would be DC. His rival, Nikola Tesla, was a believer in AC. I'll give the gruesome details (including the execution of an elephant) at the end of this chapter.

In the end, Tesla won. We use AC, not DC, and our power plants are located far away, not on every street corner. Our wall-plugs deliver 110 volts at 60 Hz. Many of our homes have a separate set of wires for 220 V, used on devices that take much more power, such as air conditioners. The higher voltage allows less current to be used for the same power, and that reduces losses from resistance. In Europe, virtually all appliances use 220 V (at 50 Hz). This higher voltage is more dangerous, but it does reduce resistive loss that turns power into heat.

Magnetic levitation

Ordinary iron, when exposed to a magnet, becomes a magnet itself, and is attracted to the original magnet. But some materials behave differently. When exposed to magnetism, they become magnets themselves, but in the opposite sense. The part which is exposed to the north pole of the magnet becomes a north pole itself, and instead of being attracted, it is repelled.

Such materials are not common, and that is why our experience is that magnets "attract" things. Liquid oxygen is one of the uncommon materials that is repelled by ordinary magnets. But superconductors are also repelled. When exposed to magnets, currents start flowing inside superconductors in just such a way as to create a repulsive force. If you place a small superconductor on top of a magnet, the force can make the superconductor "levitate" above the magnet, with the repulsive force countering gravity.

If you have a changing magnetic field, created by an electromagnet with alternating current, then levitation can be done with ordinary metals. The changing magnetism will cause currents to flow in the metal, and these currents will create magnetism that repels the original magnet. This approach can be used to levitate large objects. For a demonstration of this effect, see http://www.mip.berkeley.edu/physics/D+15+24.html.

Levitation can also be done with moving magnets. If a strong magnet (samarium cobalt, or a strong electromagnet) is moved over a conductor, then electrical currents will be induced in the conductor. Those create a magnetic field that repels the original magnet. This approach is used commercially in magnetically levitated trains in Japan. At slow velocities, there is no levitation (since the induced magnetism requires a rapidly changing, or moving electrons). As the trains moves faster, the magnet moving over the rails induces stronger and stronger currents, until finally the magnetic repulsion lifts the wheels off the tracks. The advantage of magnetic levitation is that it avoids all the friction of contact. However, the currents flowing in the rails do lose some energy to electrical resistance, and that can be a serious limitation. Superconducting rails would avoid this problem, but they have to be kept cold. With all these problems, magnetic levitation has not proven to be as successful as some futurists have predicted. That could change if we ever develop room temperature superconductors.

Rail guns

In Chapter 3 "Force and Gravity" we discussed the limitations of launching objects into space using chemical fuels. The problem was the exhaust velocity of such fuels was only 1 or 2 km/s, so it was hard to use them to push objects that had to go 11 km/s. But using magnetism, we can overcome that limit. The device that does this is called a rail gun.

The simplest version of a rail gun consists of two long parallel metal rails, just like those used for railroads. A high voltage is placed across the ends of the rails, and a piece of metal (called a sabot) is placed across or in between the two rails. High current flows from the end of one rail, down the rail, across the metal, to the second rail, and back. The high current in the rails creates a strong magnetic field, and this puts a force on the current flowing through the metal sabot. As a result, the sabot is pushed down the rails. Theoretically, rail guns can launch a sabot at extremely high velocities.

Rail guns are under development by the U.S. Navy as a way of shooting down missiles attacking a ship, and they may one day be used to launch materials from the moon.

High tension: the Edison-Tesla conflict

In the late 1800s, Thomas A. Edison had invented the light bulb. This had such a great impact on the world, that even today cartoonists use an image of a light bulb suddenly appearing above someone's head as an indication that the person had a great idea.

The man who most disliked Edison's invention was a John D. Rockefeller, who had made a fortune selling oil. At that time, oil was used almost exclusively for heating and lighting. Electricity (which could be made by burning coal--which boiled water, which ran a turbine, which ran a generator), could conceivably make his oil virtually worthless. Fortunately for him, right about that time improvements in oil-driven engine technology (in particular, the internal combustion engine) made possible a new invention: the auto-carriage, also known as the automobile. So Rockefeller's fortune was preserved.

Edison wanted to "electrify" New York City. His vision was to put metal wires on poles above the city streets to carry current to every house. Because some energy is lost in those wires (from resistance), the energy could not be transported very far. But he saw that as creating no real problem: he would place an electric power generator in every neighborhood, so the wires would never be more than a few blocks long.

Tesla

Edison had hired a very talented engineer named Nikola Tesla. But Tesla quit in a huff. Tesla claimed that Edison had patented all of Tesla's ideas in the name Edison, and had not given Tesla the monetary rewards that he had promised.

Tesla had become enamored with the idea of "alternating current," AC for short. In AC the voltage and the current oscillated, positive and then negative and then positive again, 60 times every second. If one used AC instead of Edison's DC (for "direct current") then you could make use of a wonderful invention called the transformer. (The transformer was invented in 1860 by Antonio Pacinotti. Recall that transformers used to generate extremely high voltages are often called "Tesla coils".) A transformer used the fact that a wire with current in it creates a magnetic field. If the current varies, then the magnetic field varies. A changing magnetic field will create a current in a second wire. The amazing part of all this is that the voltage in the second wire could be very different from the voltage in the first wire. What the transformer transforms is the voltage.

Start with low voltage AC, put it through a transformer, and what comes out is high voltage AC. The advantage of high voltage AC is that it carries power with very little electric current. That means that there is very little power loss in the wires, so the power can be sent for long distances using long wires. There would be no need to have electric generating plants in every neighborhood. When the electricity got close to a home, it could be transformed again, to convert the electricity to low voltage, which is less dangerous to use. A small transformer could be place on the top of the pole that supported the wires. (Most neighborhoods today have just these transformers on the pole tops. When they burn out or otherwise fail, the neighborhood is left without electricity, and the transformer must be replaced or repaired. The local electric company, such as PG&E, usually does this within a few hours.)

AC turned out to have such an advantage (no neighborhood power plants) that it completely won out over Edison's DC. Tesla got the support of George Westinghouse, and their system turned into the one we use today. The voltage in our homes is only 120 volts AC. (Actually 120 is an average voltage; the voltage varies between about -170 volts and +170 volts.) The voltage changes from positive to negative and then back to positive 60 times per second, i.e. 60 Hertz, abbreviated 60 Hz. In Europe, they use the slower frequency of 50 Hz, which is why their lights and their televisions flicker. (Our eyes don't notice flickering if it is faster than about 55 Hz. I think the Europeans made a dumb mistake, all for the purpose of trying to be a little more metric than the US. For a while, they also tried 50 seconds to the minute, and 50 minutes to the hour, but they gave up--people couldn't get used to it. But the 50 cycles per second remained.)

Electrocuting elephants and murderers

But Edison did not give up without a fight. He tried to convince the public that high voltage was too dangerous to use in cities. He did this with a series of demonstrations of the danger, in which he invited the public to watch as he used the Westinghouse/Tesla high voltage system to electrocute puppies and other small animals. Eventually he put on a demonstration using high voltage to kill a horse. Edison had also invented a motion picture camera, and so he was able to make a movie of the electrocution of an elephant. I find the movie horrifying. The name of the elephant executed was Topsy and she was a "bad" elephant who had been condemned to die for having killed three men (including one who fed her a lit cigarette). Apparently the Society for Prevention of Cruelty to Animals approved of the execution, since they thought it would be inhumane to hang Topsy. See the Topsy page for the details. In an unrelated quote, Edison said, "Non-violence leads to the highest ethics, which is the goal of all evolution. Until we stop harming all other living beings, we are still savages." I found a copy of the movie, but I don't recommend that you view it. If you can't resist, it is at available http://muller.lbl.gov/movies/Topsy.html.

The ultimate horror, of course, was to show that high voltage electricity could kill humans. To do this, Edison convinced the State of New York to switch from hanging its condemned inmates, to electrocuting them. He also argued that this method of execution was more humane--a conclusion that most modern observers think is exactly backwards. But New York adopted the method, and then so did several other states. Despite the publicity created by all these things, the advantages of AC won the day, and that is what we use now.

Optional: Automobile Battery

When you buy an automobile battery, it will have on its label the voltage, the "cold cranking" amperes, and the "reserve capacity." For a good (expensive) car battery, the numbers might look like this:

Voltage	12 V
cold cranking amperes	800 amps (at 7.2 V)
reserve capacity	120 min = 7,200 s (at 10.2 V)

These numbers are defined in a particular way. The "cold cranking amps" represents the current that the battery will deliver for 30 seconds (s), without the voltage dropping below 7.2 V. (When high current comes from the battery, the voltage of the battery drops, because of resistance within the battery itself.) Having lots of cold cranking amps is important when you are starting your car, because that is when you use the highest current. In the example above, the battery can deliver current I = 800 amps for 30 s at a voltage of V = 7.2 volts. The power it delivers is $P = V\,I$ = 12 x 800 = 9,600 W. It delivers this for 30 s. The energy it delivers is $E = P\,t$ = 9600 x 30 = 288,000 J = 70,000 cal = 70 Cal.

The "reserve capacity" is defined as the time for which the battery can deliver 25 amps of current without the voltage dropping below 10.5 V. This is important, for example, if you leave your lights on by accident when you park your car. The power is $P = V\,I$ = 10.5 x 25 = 262 W. It can deliver this for 7200 s. The energy delivered is $E = P\,t$ = 262 x 7200 = 2,000,000 J = 500,000 cal = 500 Cal. Note that the battery is MUCH more efficient at the lower current: the energy it can deliver is 500 Cal instead of only 70 (when cold-cranked).

An automobile battery weighs about 45 lb = 20,000 g. So the energy this battery can deliver per gram is 500/20,000 = 0.025 Cal/g. This is the value that we used previously when discussing the difficulties of making a useful electric car; recall that the energy stored per gram for gasoline is about 10 Cal/g, i.e. 400 times larger than for the car battery.

Optional: More on Flashlight Batteries

When you buy a flashlight battery, it doesn't give you ANY specifications except the voltage, and vague claims about it being "long lasting" or "durable." For those of you who will someday pass laws, please change that! Why can't flashlight batteries be labeled in the same manner as automobile batteries?

Looking on the Web, I found that typical "D Cell" batteries have an energy rating of 1200 milliamp hours (mAhr). That means they can deliver 1200 milliamps = 1.2 amps for 1 hr, i.e. for 3600 s. Since the voltage is 1.5 V, the power delivered in that hour would be

1.2 x 1.5 = 1.8 W. The energy is $E = P\,t$ = 1.8 x 3600 = 6480 J = 1.6 Cal. The battery weighs 135 g, so the energy is 1.6/135 = 0.01 Cal/g. This is a factor of 2.5 worse than we found for automobile batteries. So flashlight batteries, made to be safe, dry, and easily handled, have 2.5 times less energy per gram than car batteries. And they are not rechargeable.

Optional: Amp hours and Watt hours
Buying the Best Battery for Your Cell Phone, Camera, or Computer

Expensive batteries often have numbers on them that describe how much electricity they can deliver. A battery that can deliver one ampere for one hour is said to have a capacity of one amp hour. That is a typical specification for a "D cell" battery, the kind of battery that is typically used in a flashlight. Sometimes they will specify the capacity in milliamp hours. A milliamp (abbreviated 1 mA) is 1/1000 amp. So a battery with a capacity of 1000 mAhr has a capacity of 1 amp hour.

Some batteries specify instead the energy stored in a battery. That's not given in amp hours, but in watt hours, or in milliwatt hours (abbreviated mWhr). If you have an expensive battery on a computer, digital camera, or other device, look at it and see what it says. Some batteries give you the number of mAhr, and others give you the number of mWhr. They are not the same! Since a watt is a volt times an amp, and since a milliwatt is a volt times a milliamp, we can convert from one to the other by the following simple rule:

$$\text{mWhr} = \text{mAhr} \times \text{V}$$

This rule can be important when picking a battery. I have a camera battery that says it operates at 4 V. It also says its "capacity" is 1200 mAhr. I can buy another battery that says it can deliver 2400 mWhr. Which one is better? Answer: the first one. Its capacity is 1200 mAhr. To convert that to mWhr, multiply by the voltage, to get 4800 mWhr. When doing comparison shopping, it is important to use the same units.

Optional:

Here is an interesting coincidence. Suppose you let one ampere flow for a day. How many electrons total were there? One amp is 6×10^{18} electrons per second, and there are 86400 seconds per day.[12] The total number is the product of these two numbers: $6 \times 10^{18} \times 86400 = 5 \times 10^{23}$. That's almost one mole, the number of electrons in one gram of hydrogen. Think of it in the following way: if you were to take a gram of hydrogen, and remove the electrons, you would have enough to make a flow of one ampere for one day.

[12] 60 seconds per minute, 60 minutes per hour, 24 hours per day, gives 60 x 60 x 24 = 86400 seconds per day. Multiply this by 365 days per year to get 3.15×10^{7} seconds per year.

END OF CHAPTER

Quick Review

Electricity is the flow of electrons, or other similar particles that carry "electric charge." By convention, the electric charge on the electron is -1.6×10^{-19} Coulombs. The proton has an equal and opposite charge. This is a basic quantum of charge; all observed charges are multiples of this, with the exception of the quark (hidden inside the nucleus) which has 1/3 or 2/3 of this value. Atoms usually have zero net charge, since the electrons and protons balance. (If they don't, the object is called an "ion".) The flowing of charges (usually electrons) is called electric current, and is measured in amperes. One ampere is a Coulomb of charge every second. Current usually flows in loops, otherwise charge builds up and the resulting force slows the flow.

Current can flow in gases, in vacuum, and in metal. When electrons do this, they usually lose some energy, and that is called electric resistance. The power lost is determined by the current flow. Insulators are materials that are poor conductors (high resistance). Superconductors, which require very low temperatures, have resistance = 0. "High temperature superconductors" require temperatures of 150K, equal to –189 F.

Voltage measures the energy of the electrons. Power is voltage x current. High voltage is not particularly dangerous unless the current is large enough to give high power.

Batteries are rated by amp hours. That is actually the total charge they can deliver. Multiply the amp hours by voltage and you get the total energy available in watt hours.

In our homes we use AC (rather than DC) because the voltage can be changed easily using transformers. High voltage (low current) is used to bring the electricity to our homes, but the voltage is lowered to make it safer before it comes in.

The equations for electric force look similar to those of gravity. There are two laws, one for charge and one for current. The force drops with the square of the distance, so things 10x further away have 100x less force. But there are differences. Two charges with the same sign repel, and with opposite signs attract. For electrons, the electric force is much greater than gravity. When the force is between currents, we call it magnetism. Permanent magnets arise when the flow of electric charge within a large number of atoms is all in the same direction. Permanent magnets are used in magnetic compasses. No magnetic monopoles have ever been found, but the search continues. Electromagnets are made by making currents flow, typically in loops. They are used in automobile door locks, speakers, and earphones. When done in a rotary design, it is called an electric motor. Strong permanent magnets like samarium cobalt have made small earphones and motors possible. Iron, when placed in a magnetic field, strengthens the field, unless the iron is warmer than its Curie temperature. Some materials remain magnetized after being exposed to magnetic fields, and these are used for magnetic recording.

When a wire passes through a magnetic field, currents flow in the wire, and this is used for electric generators. If the current is used to make the magnetic field stronger, the generator is called a dynamo. Dynamos are used for the generation of commercial electric power. The core of the Earth has a natural dynamo, and that makes the Earth into a magnet. The magnetism of the Earth flips, on average, several times every million years. That discovery is very useful in geology for determining the age of rocks.

Transformers change voltage and current, while wasting very little power. A Tesla coil produces very high voltages.

Magnetic levitation uses repelling magnetic fields. These fields are sometimes generated by moving metal or by AC current. Rail guns can accelerate metal to high velocities more efficiently (with less wasted energy) than can rockets.

Discussion Questions

Electricity and Magnetism seem different, but electricity can create magnetism, and magnetism can create electricity. Describe how this is done. Give examples illustrating how this is used in practical applications.

Magnets make nice toys, but magnetism is also indispensable for modern life. There are numerous uses of magnetism in applications where many people in the general public do not even know that it is involved. Describe several of these, and say a few words about each one to show what the magnetism does in each case.

Discuss superconductivity. What is its value, and what are its limitations? How might it prove important in the future?

Why is the electricity from the wall AC rather than DC? Describe what important physical principles go into making the choice. Describe how this happened historically, and what you think might happen in the future.

Read the following passage, taken from *Popular Science* in 1892, and see what sense you can make of it, given the modern understanding of electricity.

> We know little as yet concerning the mighty agency of electricity. Substantialists tell us it is a kind of matter. Others view it not as matter, but as a form of energy. Others, again, reject both these views. One professor considers it "a form, or rather a mode of manifestation, of ether." Another professor demurs to the view of his colleague, but thinks that "nothing stands in the way of our calling electricity ether associated with matter, or bound ether." Higher authorities cannot even yet agree whether we have one electricity or two opposite electricities. The only way to tackle the difficulty is to persevere in experiment and observation. If we never learn what electricity is, if, like life or like matter, it should remain an unknown quantity, we shall assuredly discover more about its attributes and its functions.
>
> The light which the study of electricity throws on a variety of chemical phenomenon cannot be overlooked. The old electrochemical theory of Berzelius is superseded by a new and wider theory. The facts of electrolysis are by no means either completely detected or coordinated. They point to the great probability that electricity is atomic, that an

electrical atom is as definite a quantity as a chemical atom. The electrical attraction between two chemical atoms being a trillion times greater than gravitational attraction is probably the force with which chemistry is most deeply concerned.

--*Popular Science*, February 1892
(Quoted in the Feb 1992 edition)

Short Questions

Basic Definitions

Which of the following is incorrectly paired? (check all that are wrong)
( ) power - watts
( ) energy - kwhr
( ) resistance - ohms
( ) current - volts

Current is measured by:
( ) volts
( ) calories
( ) amps
( ) watts
( ) ohms

Ohms are a measure of
( ) current
( ) charge
( ) voltage
( ) resistance

A "volt" is a measure of
( ) energy per electron
( ) number of electrons per second
( ) force on the electron
( ) density of electrons

What is a coulomb?
( ) 6X10^18 electron charges
( ) the energy of one electron at a potential of one volt
( ) one cubic kilometer per second
( ) one ohm per second
( ) the charge on one electron

If the distance between two charges is increased by a factor of 4, what happens to the electric force?

( ) it remains the same
( ) it decreases by 2
( ) it increases by 2
( ) it decreases by 4
( ) it increases by 4
( ) none of the above

Magnetism

Magnetism comes from
( ) magnetic monopoles
( ) moving quanta of light
( ) quantization of charge
( ) moving electric charge

In a permanent magnet, the magnetism comes from:
( ) the spin of the electrons
( ) the motion of the protons
( ) the high voltage inside the atom
( ) the electron avalanche

Magnetic monopoles
( ) are found at the ends of magnets
( ) are produced by cosmic rays
( ) are found in the Earth's core
( ) have never been found

The top end of a long rod is discovered to be a north-pointing magnetic pole. The rod is broken in half. In the resulting two pieces, the number of south-seeking poles is:
( ) zero
( ) one
( ) two
( ) four

Rail guns push the projectile using
( ) high energy explosives
( ) electric fields
( ) magnetic fields
( ) protons

You can demagnitize a natural magnet
( ) by placing it on a TV or Computer screen
( ) by placing it in a very strong electric field
( ) by heating it above the Curie point
( ) none of the above

What discovery now allows for headphones to be small and light?
( ) dynamos
( ) rare earth magnets, such as samarium cobalt
( ) transformers
( ) iron

Which of the following use or consist of permanent magnets?
(check all that apply)
( ) loadstones
( ) transformers
( ) compasses
( ) earphones

The Earth's Magnetic Field

Theoretically, the Earth should not have a permanent magnetic field because:
( ) its interior is too hot
( ) the Earth spins
( ) there is not enough iron
( ) magnets do not occur naturally

The Earth's magnetism comes from
( ) a dynamo in the core
( ) permanent magnets in the core
( ) iron in the crust
( ) monopoles near (but not at) the North and South geographic poles

The Earth flips its magnetism, on average, approximately:
( ) once every 11 years
( ) twice every million years
( ) once every billion years
( ) never (at least not yet)

The Earth's magnetic flips are used for
( ) creating new permanent magnets
( ) proving the Earth has a solid iron core
( ) generate useful power
( ) geologic dating

Compasses point north because
( ) the North Star attracts them
( ) the Earth has an electric charge
( ) there are electric currents in the iron core of the Earth
( ) there are magnetic monopoles near the North Pole

The north geographic pole of the Earth
( ) is a south magnetic pole
( ) has always had the same polarity
( ) is exactly at the magnetic pole
( ) none of the above

Electricity

Electricity will heat a wire if it has
( ) high voltage
( ) high current
( ) high frequency
( ) DC rather than AC

Static electricity occurs when two surfaces rub against each other and:
( ) protons flow from one to another
( ) electrons flow from one to another
( ) positrons flow from one to another
( ) neutrons flow from one to another

Europe uses higher voltage in their homes because it
( ) creates less heat in home wiring
( ) carries greater power
( ) is less dangerous
( ) works better for DC (used in Europe instead of AC).

Lights and TVs in Europe tend to flicker because Europe uses
( ) 240 volts -- the US uses 120 volts
( ) 120 volts -- the US uses 240 volts
( ) 50 Hertz -- the US uses 60 Hertz
( ) 60 Hertz -- the US uses 50 Hertz

When an object is short of electrons, it
( ) has a negative charge
( ) has a positive charge
( ) has a low resistance
( ) glows (e.g. lightbulb wire)
.
What has the greatest resistance?
( ) You
( ) A six inch cooper wire
( ) A 12 inch copper wire
( ) A 1 meter iron rod

Why are we not harmed when we put our hands across a car battery?
( ) the battery has low energy
( ) the battery has high resistance
( ) the battery has low current
( ) we have high resistance

To get a spark, you normally need:
( ) High voltage
( ) High current
( ) Low resistance
( ) Alternating Current

In a metal, electrons
( ) are confined to a single atom
( ) always point in the same direction
( ) can move freely
( ) do not exist

The aspect of electricity that makes it dangerous is high:
( ) voltage
( ) current
( ) frequency
( ) power

A fuse is used in a house to prevent:
( ) large power surges
( ) house wires from overheating
( ) illegal use of electricity
( ) too much voltage from entering the house
( ) too much energy usage

A big generator uses its own electricity to strengthen its Magnetic field. Such a generator is called a:
( ) superconductor
( ) transformer
( ) samarium
( ) dynamo

Superconductors

The original superconductors were cooled with
( ) liquid nitrogen
( ) liquid helium
( ) Freon refrigerators

( ) hydrogen gas

Room temperature superconductors
( ) are used in advanced computers
( ) are used to carry electric power
( ) are used for strong magnets
( ) may exist, but haven't been found

"High temperature superconductors" operate at approximately:
( ) room temperature
( ) 4 K (liquid helium temperature)
( ) -123 C (liquid nitrogen)
( ) 2000 C

AC and DC

We use AC instead of DC because:
( ) 120 Volts AC is less dangerous than 120 Volts DC
( ) AC is cheaper than DC
( ) AC can use transformers
( ) DC can use transformers

Topsy was executed with AC:
( ) to show the dangers of high voltage
( ) because DC would not have worked
( ) because it was the only way to get high current
( ) AC delivers more power than DC

What invention made it possible to change low voltage AC to high voltage AC?
( ) Van de Graaff generator
( ) samarium-cobalt magnets
( ) electron beam
( ) transformer

Edison wanted
( ) a power plant on every corner
( ) high voltage DC
( ) alternating current
( ) to abolish the electric chair

Miscellaneous

The current through a flashlight bulb is approximately:
( ) 120 amp
( ) 1.6 x10^-19 amp
( ) one amp

( ) 15 amp

A high-fidelity stereo speaker produces sound by:
( ) the force of a magnetic field on electric current
( ) the force of an electric field on an electric charge
( ) the force of a magnetic field on an electric charge
( ) the force of an electric field on a magnetic charge

The light from an ordinary light bulb comes from the fact that:
( ) the wire contains phosphor
( ) the wire is heated by electricity
( ) the high voltage causes small sparks
( ) electricity is a wave

A Tesla coil is a kind of
( ) transformer
( ) dynamo
( ) radio transmitter
( ) sensor for the Curie point

The Tesla coil was useful because:
( ) it allowed there to be a powerplant in every neighborhood.
( ) it made the high voltage less dangerous
( ) it decreased the current going through long wires to reduce the loss of electricity.
( ) it was given strong support by Thomas Edison, who popularized it

Submarines can be detected by their
( ) magnetism
( ) electric charge
( ) backscattered xrays
( ) MRI signal

The "Curie Temperature" is the temperature at which:
( ) molecular movement stops.
( ) fusion takes place in the sun
( ) magnetism disappears
( ) fission takes place in a bomb

Most electric power is generated by
( ) static electricity
( ) a wire moving through a magnetic field
( ) moving a wire in a strong electric field
( ) chemical means (batteries or fuel cells)